METHODS AND SYSTEMS FOR SELECTIVE INTERLEAVING IN RETRANSMISSIONS AND ITERATIVE DEMODULATION OF MODULATED SIGNALS WITH DIFFERENT INTERLEAVING

BACKGROUND OF THE INVENTION

The present invention relates to signal communications and, in particular, to signal communications utilizing retransmission of messages.

One type of communications channel for which usage is expanding particularly rapidly is wireless communications, particularly as more radio spectrum becomes available for commercial use and as cellular phones become more commonplace. In addition, analog wireless communications are gradually being supplemented and even replaced by digital communications. In digital voice communications, speech is typically represented by a series of bits which may be modulated and transmitted from a base station of a cellular communications network to a mobile terminal device such as a cellular phone. The phone may demodulate the received waveform to recover the bits, which are then converted back into speech. In addition to a growing demand for voice communications, there is also a growing demand for data services, such as e-mail and Internet access, which typically utilize digital communications.

There are many types of digital communications systems. Traditionally, frequency-division-multiple-access (FDMA) is used to divide the spectrum up into a plurality of radio channels corresponding to different carrier frequencies. In time division multiple access (TDMA) systems, carriers may be divided into time slots, as is done, for example, in the digital advanced mobile phone service (D-AMPS) and the global system for mobile communication (GSM) standard digital cellular systems. Alternatively, multiple users can use a common range of frequencies using spread-spectrum techniques as is typically done in code-division multiple-access (CDMA).

A typical digital communications system **19** is shown in **Figure 1**. Digital symbols are provided to the transmitter **20**, which maps the symbols into a representation appropriate for the transmission medium or channel (*e.g.* radio channel) and couples the signal to the transmission medium via antenna **22**. The transmitted signal passes through the channel **24** and is received at the antenna **26**. The received signal is passed to the

receiver **28**. The receiver **28** includes a radio processor **30**, a baseband signal processor **32**, and a post processing unit **34**.

The radio processor **30** typically tunes to the desired band and desired carrier frequency, then amplifies, mixes, and filters the signal to a baseband. At some point the signal may be sampled and quantized, ultimately providing a sequence of baseband received samples. As the original radio signal generally has in-phase (I) and quadrature (Q) components, the baseband samples typically have I and Q components, giving rise to complex, baseband samples.

The baseband processor **32** may be used to detect the digital symbols that were transmitted. It may produce soft information as well, which gives information regarding the likelihood of the detected symbol values. The post processing unit **34** typically performs functions that depend on the particular communications application. For example, it may convert digital symbols into speech using a speech decoder.

A typical transmitter is shown in **Figure 2**. Information bits, which may represent speech, images, video, text, or other content material, are provided to forward-error-correction (FEC) encoder **40**, which encodes some or all of the information bits using, for example, a convolutional encoder. The FEC encoder **40** produces coded bits, which are provided to an interleaver **42**, which reorders the bits to provide interleaved bits. These interleaved bits are provided to a modulator **44**, which applies an appropriate modulation for transmission. The interleaver **42** may perform according to one of a number of types of interleaving.

The modulator **44** may apply any of a variety of modulations. Higher-order modulations are frequently utilized. One example is 8-PSK (eight phase shift keying), in which 3 bits are sent using one of 8 constellation points in the in-phase (I)/ quadrature (Q) (or complex) plane. Another example is 16-QAM (sixteen quadrature amplitude modulation), in which 4 bits are sent at the same time. Higher-order modulation may be used with conventional, narrowband transmission as well as with spread-spectrum transmission. The Enhanced Data Rates for Global Evolution (EDGE) standard generally uses Gray mapping from triplets to 8-PSK symbols. As a further example, the Global System for Mobile communications (GSM) typically uses non-linear modulation.

One particular type of wireless communication for interconnection of devices, known as Bluetooth™, is directed to providing a relatively robust high-speed wireless connection with low-power consumption and a low-cost architecture. Bluetooth technology may provide a universal radio interface in the 2.45 GHz frequency band to

enable portable electronic devices to connect and communicate wirelessly via short-range ad hoc networks. Bluetooth technology is generally targeted towards the elimination of wires, cables, and connectors between such devices and systems as cordless or mobile phones, modems, headsets, personal digital assistants (PDAs), computers, printers, projectors, and local area networks. The Bluetooth interface is further described in an article authored by Jaap Haartsen entitled *Bluetooth--The universal radio interface for ad hoc, wireless connectivity,* Ericsson Review, No. 3, 1998, which is hereby incorporated herein by reference.

Robust high-speed wireless connections with low-power consumption and low-cost architecture, such as Bluetooth, often place special requirements on system designs. On the one hand, sophisticated coding and signal processing techniques may be desired to combat adverse fading environments. On the other hand, the emphasis on low cost and power as well as high through-put may reduce the usefulness of these techniques. Automatic request retransmission (ARQ), schemes with little or no error correction coding, may offer the best trade-offs for such an environment.

In a conventional ARQ system, a retransmission is typically requested when a frame is found to be erroneous. There are generally two ways to combine the two copies of signals. The first approach combines the matched filter outputs coherently and feeds the results to the demodulator. A second approach is to demodulate the two copies separately and then combine the soft values that are provided by the demodulator. Both techniques generally conform to the principle of maximum ratio combining (MRC), as described, for example, in J. G. Proakis, *Digital Communications*, 2nd ed., Chapter 7, 1989. Such systems may provide good performance under fading channels.

Typical link-level performance of this ARQ with MRC scheme is shown in **Figure 11** where the underlying modulation is assumed to be uncoded differential binary phase shift keying (DBPSK). Frame-wise flat Rayleigh fading is assumed. That is, each transmitted frame is multiplied by a Gaussian distributed fading coefficient and the fading is independent from frame to frame. As shown in **Figure 11**, with more and more retransmissions, the probability of a correct reception is increased. For example, at C/N = 10 dB, there is a 60% chance that the frame will be wrong and retransmissions will be needed. With two copies received, there is still a 30% chance that more retransmission will be needed.

SUMMARY OF THE INVENTION

In embodiments of the present invention, methods and systems for iterative demodulation of a message are provided. A first copy of the message is received to provide a first set of symbols associated with the message. A second copy of the message is received to provide a second set of symbols. The first copy is associated with a first interleaving pattern and the second copy is associated with a second interleaving pattern different from the first interleaving pattern. The first set of symbols and the second set of symbols are iteratively demodulated using extrinsic information associated with the first set of symbols for demodulation of the second set of symbols and extrinsic information associated with the second set of symbols for demodulation of the first set of symbols to provide a set of symbol estimates for the message. Transmit methods and systems for selective interleaving to generate the copies of the message in a retransmission based communication system are also provided.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a block diagram illustrating a conventional communication system;

Figure 2 is a block diagram illustrating a conventional transmitter;

Figure 3 is a block diagram illustrating a mobile terminal including iterative demodulation and selective interleaving according to embodiments of the present invention;

Figure 4 is a block diagram illustrating a base station system including iterative demodulation and selective interleaving according to embodiments of the present invention;

Figure 5 is a block diagram illustrating a receiver device including iterative demodulation according to embodiments of the present invention;

Figure 6 is a block diagram illustrating a transmitter device including selective interleaving according to embodiments of the present invention;

Figure 7 is a flowchart illustrating receiver operations for an incremental redundant differential modulation according to embodiments of the present invention;

Figure 8 is a flowchart illustrating receiver operations for iterative demodulation according to embodiments of the present invention;

Figure 9 is a flowchart illustrating selective interleaving retransmission operations according to embodiments of the present invention;

Figure 10 is a flowchart illustrating operations for iterative demodulation according to embodiments of the present invention;

Figure 11 is a graphical illustration of link-level performance for a conventional automatic repeat request (ARQ) system with maximum ratio combining (MRC);

Figure 12 is a graphical illustration of link-level performance for an incremental redundant differential modulation system according to embodiments of the present invention;

Figure 13 is a graphical illustration of average through-puts for a conventional ARQ system and for an incremental redundant differential modulation system according to embodiments of the present invention; and

Figure 14 is a graphical illustration of average number of differential demodulation passes for incremental redundant differential modulation systems according to embodiments of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. As will be appreciated by those of skill in the art, the present invention may be embodied as methods or devices. Accordingly, the present invention may take the form of a hardware embodiment, a software embodiment or an embodiment combining software and hardware aspects.

Figure 3 illustrates a mobile or wireless terminal **300** in which systems and methods according to the present invention may be embodied. The terminal **300** includes an antenna **310** for receiving radio frequency (RF) signals. The terminal **300** provides a user interface including a display **320** for displaying information such as dialed numbers, short messages, directory listings and the like, and a keypad **330** for entering dialed numbers and accepting other user inputs for controlling the terminal **300**. The user interface also includes a speaker **340** for producing audio signals and a microphone **350** for receiving voice information from a user. The terminal **300** also includes a controller **360** that controls and/or monitors the display **320**, the keypad **330**, the speaker **340**, the microphone **350** and a radio transceiver **370** tied to the antenna **310**.

The controller **360** may include, for example, a microprocessor, microcontroller or other data processing device that is operative to load and execute computer instructions for performing functions relative to selective interleaving and iterative demodulating as will be described herein. Note that various embodiments of iterative demodulating of selectively interleaved copies of a message using differential modulation will be referred to as incremental redundant differential modulation (IRDM) herein.

Figure 4 illustrates a base station system **400** of an exemplary wireless communications infrastructure including selective frequency hopping in accordance with embodiments of the present invention. A base transceiver station (BTS) **420** is operatively associated with one or more antennas **412** on a cellular base station tower **410**. The BTS **420** includes one or more radio transceivers **422** that are operative to transmit and receive communications signals via the antenna **412** under the control of a controller **424**, which may comprise, for example, a microprocessor, microcontroller, computer or other data processing apparatus. The BTS **420** is also operatively associated with a base station controller (BSC) **430** that controls radio and other operations of the BTS **420** and, perhaps, additional BTSs (not shown). As will be described below, components of the infrastructure **400** may be used for transmission and reception of communications signals, as well as for selective interleaving and iterative demodulation as will be described herein and may, thus, communicate with devices such as the terminal **300** of **Figure 3**.

Referring now to **Figure 5**, aspects of a mobile terminal such as that illustrated in **Figure 3** or a base station system such as that illustrated in **Figure 4** related to selective interleaving and iterative demodulating according to embodiments of the present invention will now be further described. As shown in the block diagram of **Figure 5**, a receiver station **500** using selective interleaving in a retransmission communication based system includes a transceiver or receiver **510** that receives copies, including an original and retransmission copies, of a transmit message and provides a set of symbols associated with the transmitted message for the received copies of the transmit message. While not shown in **Figure 5**, as with reference to **Figures 3** and **4**, it is to be understood that the transceiver **510** may be coupled to an antenna to receive and/or transmit communication messages.

The receiver station **500** further includes an iterative demodulator **515** that demodulates the provided symbol sets for receive copies of the transmit message. For example, a first copy associated with a first interleaving protocol (for example, the trivial

(no interleaving) case) may be used to produce a first set of symbols and a second copy associated with a second interleaving protocol may be utilized to provide a second set of symbols for demodulation by the iterative demodulator **515**. The iterative demodulator **515** demodulates the first set of symbols and the second set of symbols using extrinsic information associated with the first set of symbols for demodulation of the second set of symbols and extrinsic information associated with the second set of symbols for demodulation of the first set of symbols to provide a set of symbol estimates for the message. While described generally with reference to a single copy of a transmit message for each of two interleaved patterns, it is to be understood that the present invention applies as well to three or more different interleaving patterns associated with different received copies of the transmit message and further encompasses embodiments in which a plurality of copies are received of a transmit message for one or more of the selected interleaving patterns.

As shown in the embodiments of **Figure 5**, the receiver station **500** further includes an error detection circuit **535** that determines if a received message is received without error. The transceiver **510** may then further include a transmitter portion that transmits a request for retransmission to a transmitter station providing copies of the transmit message responsive to the error detection circuit **535** detecting an error in a received message.

The iterative demodulator **515** may include a demodulator circuit **520** as shown in **Figure 5** where the demodulator circuit **520**, in various embodiments, is a soft-input soft-output differential demodulator configured to demodulate transmit messages modulated using a differential modulation protocol.

Referring again to **Figure 5**, the illustrated embodiments of the iterative demodulator **515** further include a combiner circuit **525** and an ordering circuit **530** which may be incorporated within or separate from the iterative demodulator **515**. The combiner circuit **525** is configured to provide one set of symbols to the demodulator circuit **520** based on copies of a transmit message associated with the first interleaving protocol and one set of symbols to the demodulator circuit **520** based on copies of the transmit message associated with a second, different, one of a plurality of interleaving protocols. In various embodiments of the present invention, the combiner circuit **525** selects a single set of symbols by selecting the most recently received copy of a transmit message associated with each different interleaving protocol. In alternative embodiments of the present invention, the combiner circuit **525** provides a single

associated set of symbols to the demodulator circuit **520** for demodulation based on a combining algorithm. For example, the combining algorithm may comprise maximum ratio combining.

The ordering circuit **530** provides a means for ordering a set of symbols associated with one interleaving protocol and extrinsic information associated with other interleaving protocols available at the receiver station **500** so that the respective extrinsic information and received symbol sets have a corresponding order. This order may then be used to facilitate operations of the demodulator circuit **520** to generate extrinsic information from demodulation of a set of symbols associated with a first interleaving protocol based on extrinsic information generated from processing of received set of symbols associated with one or more other interleaving protocols for which received symbol sets are available at the receiver station **500**.

Note that, for the initial pass through the demodulator circuit **520** of the first set of symbols to be processed, the extrinsic information for each received set of symbols may be initialized to a value, such as all zeros, if no *a priori* information is available from any other source. Furthermore, it is to be understood that the ordering circuit **530** may provide for a corresponding order by reordering extrinsic information and/or reordering of the received symbol sets. Furthermore, as noted above, demodulation of each set of symbols for a given interleaving pattern may be based on extrinsic information available for all other interleaving patterns for which information is available at the receiver station **500** or may be based on a subset of such extrinsic information.

It is to be understood that the iterative demodulator circuit **515** as described with reference to **Figure 5** may be, for example, implemented in the controller **360** of the mobile terminal **300** illustrated in **Figure 3**. Furthermore, the operations of the iterative demodulator circuit **515** of **Figure 5** may also be implemented at various devices within the base station system illustrated in **Figure 4**. For example, such operations may be supported by the controller **424** of the BTS, by the BSC **430** or the mobile switching center (MSC/MTSO). Furthermore, such operations may, where appropriate, be distributed across various of the component controllers which may be included in different base station systems.

Referring now to the block diagram illustration of **Figure 6**, a transmitter station **600** according to embodiments of the present invention will now be further described. The transmitter station **600** includes an interleave circuit **610**, an interleave selection

circuit **615** and a transmitter **620**. The illustrated transmitter station **600** further includes a receiver **625** and a retransmission circuit **630**. The transmitter **620** and receiver **625** may be combined as a transceiver.

The interleave circuit **610** applies a selected one of a plurality of interleaving protocols (patterns) to a copy of a message to be transmitted. The interleave selection circuit **615** selects one of the plurality of interleaving protocols for an original copy of a transmit message and another for retransmission copies of the transmit message. In accordance with the selective interleaving aspects of the present invention, at least two different interleaving patterns are applied to different transmitted copies of a message. For example, the interleave selection circuit **615** may be configured to alternate transmitted copies of the transmit message between a first one of the interleaving protocols, such as the trivial (no interleaving) case, and a second one of the interleaving protocols specifying interleaving before transmission. Thus, the original transmission and a second retransmission copy may be sent with no interleaving and a first retransmission copy and a third retransmission copy may be provided with a specified interleaving pattern, and so on for additional retransmission copies. A greater number of interleaving protocols may be selected although the present inventors have found that the benefits of the present invention may generally be achieved with as few as two or three protocols which may simplify operations of the interleave selection circuit **615** and the interleave circuit **610** by reducing the number of different interleaving patterns to be applied. While operations generally will be described herein as alternating between the selected patterns, the present invention is not so limited and other sequences of interleaving protocols for transmit copies may be provided so long as copies from a plurality of interleaving protocols are provided to the target receiver station.

The transmitter **620** transmits the respective copies of the transmit message. The retransmission circuit **630** is configured to determine whether a retransmission copy of a transmit message is to be transmitted. Such determination may be generated responsive to a received request for retransmission of a message received by the receiver **625**.

Operations of the interleave selection circuit **615** may proceed as follows. If the frame (message) to be transmitted is new (*i.e.*, it is not a retransmission frame), the frame is passed through unmodified by the interleave circuit **610** at the direction of the interleave selection circuit **615**. Thus, in this case, the transmitter station **600** behaves similarly to a conventional ARQ system. For the simplicity of notation, let this trivial (*i.e.*, none) interleaving pattern be denoted as IP(1). If the frame is to be transmitted for

the K-th time with K>1 (*i.e.*, it is a retransmission frame), the frame is interleaved by the interleave circuit **610** according to interleaving pattern IP (K) selected by the interleave selection circuit **615**. Note that the interleaving patterns do not need to all be distinct. Experiments by the present inventors indicate that two to three distinct patterns (where the trivial pattern may be one of these) are enough.

It is to be understood that methods and systems according to the present invention may be utilized in a variety of communication devices, including wireless communication devices such as wireless mobile terminals. Such a mobile terminal may include a transmitter, a receiver, a user interface and an antenna system as illustrated in **Figure 3**. By way of background, the transmitter typically converts the information which is to be transmitted by the mobile terminal into an electromagnetic signal suitable for radio communications. The receiver demodulates electromagnetic signals which are received by the mobile terminal so as to provide the information contained in the signals to the user interface in a format which is understandable to the user. The receiver generally includes an RF processor and a baseband processor. A wide variety of transmitters, receivers, and user interfaces (*e.g.*, microphones, keypads, displays) which are suitable for use with handheld radiotelephones are known to those of skill in the art, and such devices may be implemented in a radiotelephone including selective interleaving and/or iterative demodulation in accordance with the present invention. Other than the aspects related to the present invention, the design of such a radiotelephone is well known to those of skill in the art and will not be further described herein. It is further to be understood that the present invention is not limited to radiotelephones and may also be utilized with other wireless and wired communication receivers. Also, the present invention may be applied to only one communication direction, in which case both devices need not include both transmitter and receiver aspects of the present invention.

The present invention is generally described herein in the context of a wireless terminal or mobile terminal. As used herein, the term "wireless terminal" or "mobile terminal" may include, but is not limited to, a cellular radiotelephone with or without a multi-line display; a Personal Communications System (PCS) terminal that may combine a cellular radiotelephone with data processing, facsimile and data communications capabilities; a PDA that can include a radiotelephone, pager, Internet/intranet access, Web browser, organizer, calendar and/or a global positioning system (GPS) receiver; and a conventional laptop and/or palmtop receiver or other appliance that includes a

radiotelephone transceiver. Wireless terminals may also be referred to as "pervasive computing" devices and may be mobile terminals. Such devices using a low or no encoding protocol, such as Bluetooth, may particularly benefit from the present invention.

Operations for baseband receiver processing according to embodiments of the present invention are shown in **Figures 7** and **8**. For the description of **Figures 7** and **8**, a differential BPSK (DBPSK) system will be used as an example to describe operations for iterative processing. However, the present invention can be readily adapted by those of skill in the art and applied to other modulation systems, including other differential modulation schemes such as differential quadrature phase shift keying (DQPSK) and differential 8-phase shift keying (D8-PSK). Furthermore, the present invention may be used in systems using non-differential modulation protocols although the benefits of the present invention may be particularly advantageous in differential modulation protocol systems and will be described herein primarily with reference to such differential systems.

Operations for iterative demodulation according to various embodiments of the present invention will now be further described with reference to the flowchart illustration of **Figure 7**. As shown for the embodiments of **Figure 7**, all received copies of an information frame (message) are iterative demodulated (block **700**). It is then determined if the received frame was received correctly (*e.g.*, without error) (block **705**). Note that, for the illustrated operations in **Figure 7**, the symbol set for each interleaving pattern is demodulated at block **700** using extrinsic information from other received copies before determining if the frame was received without error. However, it is to be understood that, in other embodiments of the present invention, checking for successful receipt of a message, for example, after each iteration pass of a copy of a received message, may be provided.

If a frame is received correctly (block **705**), the demodulated frame information is output (block **715**). If a frame is not received correctly (block **705**), a request for retransmission of the frame is sent to the transmitter station from which the original copies of the message have been received (block **710**). If further frames remain to be processed (block **720**), operations return to block **700** and repeat as described above.

Figure 8 provides a detailed flowchart of operations according to particular embodiments of the present invention. Suppose there are L received copies of a particular frame to be processed. Let $R_m(n)$ (where m = 1, 2, …., L and n = 1, 2, …., N)

denote the soft symbol sequences from the radio frequency processing circuitry of the transceiver **510**. Assume positive values of these sequences represent ones and negative values represent zeros. For the embodiments shown in **Figure 8**, L extrinsic information buffers may be provided for each of the L received copies. Let $E_m(n)$ (where M = 1, 2, …, L and n = 1, 2, …, N) denote these values. Initially, these values are initialized, for example, to all zeros, at block **800**. However, in the case of retransmission, the extrinsic values from previous demodulation can also be used as the initial values (block **800**).

A number K from 1, 2, … , L is selected for a copy number (block **805**). There are various alternative ways suitable for this selection. First, K = 1 may always be selected. Alternatively, K may be selected to be the number of the most recent received copy. The *a priori* values V(n) (where n = 1, 2, … , N) for copy K are computed from the extrinsic values of all other copies (block **810**). This may be accomplished by computing a V(n) as:

$$V(n)=\left(\sum_{m=1}^{L}E_m(n)\right)-E_K(n)\ \ for\, n=1,2,\ldots,N. \qquad [1]$$

where V(n) is the sum of all $E_m(n)$ except for m=K.

The interleaving pattern IP(K) is applied on the sequence V(n) (where n=1,2,… , N). The copy (K) is differentially demodulated (block **815**). Any soft-input, soft-output differential demodulation algorithm that combines received symbols and a priori values to produce extrinsic values can be used here. Examples are described in C. Berrou, A. Glavieux, and P. Thitimajshima, "Near Shannon Limit Error-Correcting and Decoding: Turbo-Codes," *Proceedings of IEEE International Communications Conference '93*, pp. 1064-1070, May 1993 and D.J.C. MacKay, R.J. McEliece, and J-F Cheng, "Turbo Decoding as an Instance of Pearl's 'Belief Propogation' Algorithm," *IEEE Journal on Selected Areas in Communications*, Vol. 16, pp. 140-152, Feb. 1998. Two general principles typically guide the design of these algorithms: the BCJR and the belief propagation algorithms as described in L.R. Bahl, J. Cocke, F. Jelinek, and J. Raviv, "Optimal Decoding of Linear Codes for Minimizing Symbol Error Rate," *IEEE Transactions on Information Theory*, Vol. 20, pp. 284-287, Mar. 1974 (describing BCJR decoding) and D.J.C. MacKay, R.J. McEliece, and J.-F. Cheng, "Turbo Decoding as an Instance of Pearl's 'Belief Propogation' Algorithm," *IEEE Journal on Selected Areas in Communications*, Vol. 16, pp. 140-152, Feb. 1998. Under these two main principles, there are many techniques to simplify or speed-up the implementation of these and

processes as described for example, in P. Robertson, E. Villebrun, and P. Hoeher, "A Comparison of Optimal and Sub-Optimal MAP Decoding Algorithms Operating in the Log Domain," *Proceedings of IEEE International Communications Conference '95*, pp. 1009-1013, June 1995; S. Benedetto, G. Montorsi, D. Divsalar and F. Pollara, "Soft-Output Decoding Algorithms in Iterative Decoding of Turbo Codes," *The Telecommunications and Data Acquisition Progress Report*, Jet Propulsion Laboratory, California Institute of Technology, Vol. 42-124, pp. 63-87, Feb. 1996; and J.-F. Cheng and T. Ottosson, "Linearly Approximated Log-MAP Algorithms for Turbo Decoding," to appear in *Proceedings in IEEE Vehicular Technology Conference '00 Spring*, May, 2000. An efficient demodulation algorithm for DBPSK proposed by the present inventors will now be used for purposes of this description. However, the method can be readily adapted and applied to other differential modulations.

Operations at block **815** for this exemplary algorithm are as follows. First, tentative extrinsic values are computed using a forward recursion:

$$E\ (1) := -\infty$$
$$For\ n = 1, 2, \ldots, N-1,$$
$$E_K(n+1) := R_K(n) + MAX*\left(E_K(n), V(n)\right) - MAX*\left(E_K(n) + V(n), 0\right); \quad [2]$$
$$End$$

where - ∞ represents a large-magnitude negative number allowed in the specific processor.

The operation MAX* can be implemented in many ways. One such way is:

$$MAX*(x, y) = \max(x, y) \quad [3]$$

where this operation is equivalent to finding the maximum of the two arguments. More elaborate and exact implementations of this operation are discussed in P. Robertson, E. Villebrun, and P. Hoeher, "A Comparison of Optimal and Sub-Optimal MAP Decoding Algorithms Operating in the Log Domain," *Proceedings of IEEE International Communications Conference '95*, pp. 1009-1013, June 1995; and J.-F. Cheng and T. Ottosson, "Linearly Approximated Log-MAP Algorithms for Turbo Decoding," to appear in *Proceedings of IEEE Vehicular Technology Conference '00 Spring*, May, 2000.

The extrinsic values are then refined with a backward recursion:

$Beta$:=0; [4]

$For\ n$=N, N-1, . . . , 1,

$E_K(n) := MAX*(E_K(n), R_K(n) + Beta) - MAX*(E_K(n) + R_K(n) + Beta, 0);$

Beta := MAX(V(n), $R_K(n)$ + Beta) - MAX*(V(n) + $R_K(n)$ + Beta, 0)*;

End

Finally, the extrinsic values $E_K(n)$ (where n = 1, 2, … , N) are de-interleaved according to the interleaving pattern IP(K).

Decision values for the frame (message) are then computed (block **820**). The hard decisions *d(n)* (where n = 1, 2, … , N), in various embodiments, are based on the extrinsic values of all received copies. That is,

$$For\ n=1,2,\ldots,N, \qquad \hat{d}(n)=\begin{cases} 1\ if \sum_{m=1}^{L} E_m(n) \geq 0 \\ 0\ if \sum_{m=1}^{L} E_m(n) > 0 \end{cases} \qquad [5]$$

The cyclical redundancy checksum (CRC) in the frame is computed to determine its correctness (block **825**). If the CRC fails (block **825**), iterative decoding (by looping back through blocks **820-825**) can be invoked if there are multiple copies available for the frame. If there is only one copy available (block **830**) retransmission can be requested. Each time differential demodulator operations at block **815** are executed, a counter may be incremented. Because of the possible constraints on processing time or power consumption, a certain maximum number of demodulation passes may be allowed for each of the received copies. Once this maximum is achieved (block **835**), the iterative algorithm will be aborted and a retransmission can be requested. To begin an iterative decoding pass, a next available copy of the frame is selected for demodulation (block **840**).

As described above, a small number of patterns is used to help reduce the complexity of both the transmitter and the receiver. Note also that the first interleaving pattern IP(1) is trivial and, hence, need not be stored or programmed. Assume three interleaving patterns are used in the system. The transmitter can apply these patterns to retransmissions in a round robin fashion. That is, the first three transmissions of a frame use IP(1), IP(2) and IP(3) consecutively. The fourth transmission then uses IP(1) and so on. On the receiver side, received copies corresponding to the same interleaving patterns can be coherently combined. Therefore, the receiver only needs to maintain three buffers for the soft symbol sequences. Namely, during the first three received copies, the parameter L (the available number of copies) in the iterative algorithm is gradually increased from one to three. For the fourth received copy, the soft symbol sequence is

coherently combined with the first received copy. Thus, the parameter L will stay at three but copy number one will be flagged as a new copy for demodulation.

Operations for selective interleaving in a retransmission based communication system according to embodiments of the present invention from the perspective of the transmitter station will now be further described with reference to the flowchart illustration of **Figure 9**. As shown in **Figure 9**, operations begin with a determination of whether a copy of a message to be transmitted is a retransmission copy of the message (block **900**). Thus, if message transmission operations relate to transmission of a first copy of a message (block **900**), the message is generated for transmission using a first interleaving protocol (block **905**). The message is then transmitted to a destination device (block **910**).

If the message is being transmitted responsive to a received request for retransmission of the message (block **900**), a next protocol, such as a second interleaving protocol, is selected for retransmission of the message (block **915**). The next protocol is selected so that different copies of the message are transmitted using at least two different interleaving protocols in accordance with selective interleaving aspects of the present invention. As noted previously, for example, operations at block **915** for selecting a next protocol may include alternating between the first interleaving protocol and the second interleaving protocol for successive ones of the retransmission copies. A retransmit copy of the message is generated for transmission using the interleaving protocol selected at block **915** (block **920**). For example, after the initial transmission of the message, the copy generated at block **920** may be generated using the second interleaving protocol. However, as noted above, on subsequent passes for retransmissions, the original protocol used for transmission of the original copy of the message at block **910** may be applied to retransmission copies as well. The retransmit copy is transmitted to the destination device (block **925**). If more messages remain for transmission (block **930**), operations return to block **900** and proceed as described above.

Operations related to receiver station operations at a destination device for iterative demodulation in accordance with various embodiments of the present invention will now be further described with reference to the flowchart illustration of **Figure 10**. As shown in **Figure 10**, operations begin with receipt of a plurality of message copies at block **1000**. For simplicity of explanation herein, it will be assumed that at least a first copy of the message is received to provide a first set of symbols associated with the message and a second copy is received to provide a second set of symbols associated

with the message wherein the respective copies are associated with different interleaving patterns. It is also to be understood that a third copy may be received as well as further numbers of copies and that more than two interleaving protocols may be applied.

As shown in **Figure 10**, in various embodiments of the present invention, combine operations are applied to multiple copies of a received message. For example, where two different interleaving protocols are used for the transmitted copies of the message, a first group of copies are received associated with the first interleaving protocol and a second group of copies are received which are associated with the second interleaving protocol. The corresponding first set of received symbols and second set of received symbols are generated by combining the received copies (block **1005**). The first group and the second group may be combined at block **1005** to provide the respective first and second set of symbols. For example, in various embodiments, combining is provided by selecting a most recent one of each group to provide the respective set of symbols associated with that interleaving protocol and ignoring older copies. In alternative embodiments, the copies within each group may be combined based on a combining algorithm to provide corresponding sets of received symbols. For example, the combining algorithm may comprise maximum ratio combining.

Iterative demodulation operations will now be described with reference to blocks **1010-1035** for a case where two different interleaving protocols are provided so that a first set of symbols associated with the first interleaving protocol is to be demodulated along with a second set of symbols associated with a second interleaving protocol. However, it is to be understood that the description herein can be readily extended to the case of three sets of symbols associated with three different interleaving protocols and so on. In the first pass through operations at block **1010**, extrinsic information related to the second copy may be available at the receiver station or may be set to a default initial value to begin operations. The first copy is then demodulated to provide extrinsic information associated with the first set of symbols of the first copy (block **1010**).

For the illustrated embodiments, the extrinsic results may be tested to determine if they indicate successful receipt of the message prior to demodulation of the second copy (block **1015**). However, it is to be understood that the present invention is not so limited and the results need not be checked for error free reception after each pass through demodulation.

In any event, if the received result is not indicated as being received without error (block **1015**) (or in various embodiments where each received copy is demodulated

before checking for correct reception), the second set of symbols and the extrinsic information associated with the first set of symbols generated at block **1010** are ordered based on the first interleaving protocol and the second interleaving protocol so that the second set of symbols and the extrinsic information associated with the first set of symbols have a corresponding order (block **1020**). The second set of symbols is then demodulated based on the second set of symbols and the extrinsic information associated with the first set of symbols to provide extrinsic information associated with the second set of symbols (block **1025**).

If it is determined that the resulting extrinsic information represents a received copy of the message without error (block **1030**), the resulting extrinsic information is provided as a set of symbol estimates for the message. If the extrinsic information does not represent an error free estimate of the received message (block **1030**), iterative demodulation operations continue.

Note that in the illustrated embodiment of **Figure 10**, a retry count limit is provided. If no more retries for the iterative demodulation pass remain (block **1035**) a request for retransmission is sent to the transmitter station providing the message (block **1040**). If more retries remain (block **1035**), operations return to block **1020** for a redemodulation of the first set of symbols by ordering the first set of symbols and the extrinsic information associated with the second set of symbols generated at block **1025** based on the first interleaving protocol and the second interleaving protocol so that the first set of symbols and the extrinsic information associated with the second set of symbols have a corresponding order. The first set of symbols is then again demodulated based on the first set of symbols and the extrinsic information associated with the second set of symbols to provide updated extrinsic information associated with the first set of symbols (block **1025**).

The determination of whether a result is acceptable at block **1030** may utilize a hard acceptance criterion, such as a cyclical redundancy check error detection determination, or may be based on soft information from the demodulation process satisfying the acceptance criterion. Thus, operations continue to repeat for iterative demodulating, including, where necessary, requests for retransmission of additional copies, until the acceptance criterion is satisfied or operations are abandoned and the message is designated as unreceivable. For example, after a maximum number of demodulation passes having occurred based on a maximum number of retransmission

requests, operations may cease without provision of a set of symbol estimates for the message.

While operations above were described for the case of two interleaving protocols, the iterative demodulation of the present invention may be readily extended to three or more interleaving protocols. In such cases, the demodulation of respective sets of symbol estimates may be based on the extrinsic information associated with one or more of the other interleaving protocols. Thus, for example, demodulation operations at block **1025** in various passes may include demodulating the first set of symbols associated with the first interleaving protocol using extrinsic information associated with the second set of symbols associated with the second interleaving protocol and a third set of symbols associated with a third interleaving protocol different from the first and second interleaving protocols. Similarly, the second set of symbols may be demodulated based on extrinsic information associated with the first set of symbols and the third set of symbols and the third set of symbols may be demodulated based on extrinsic information associated with the first set of symbols and the second set of symbols. In such cases, ordering operations at block **1020** will include ordering the set of symbols to be demodulated on a particular pass and the extrinsic information associated with the two other interleaving protocols so that all three have a corresponding order.

The benefits of the present invention may be further understood by comparison of the graphical illustrations of **Figure 12**, which illustrates link-level performance for an incremental redundant differential modulation system according to embodiments of the present invention as described above, and the graphical illustration of **Figure 11** which illustrates exemplary link-level performance for a conventional automatic repeat request (ARQ) system with maximum ratio combining (MRC).

Figures 11 and **12** compare the link-level frame error rates (FER) of the two systems. Note that, as the performance illustration shown in **Figures 11** and **12** are based on a common uncoded DBPSK modulation protocol for comparison purposes, the performance of single-copy reception in accordance with the present invention corresponds to that shown in **Figure 11** for an exemplary conventional system. However, the IRDM (incremental redundant differential modulation) system outperforms the conventional ones when there are multiple copies available. For example, at FER=10%, the IRDM system is 4.5dB, 5.5dB and 6dB better when there are two, three and four copies available, respectively.

The average through-put of the IRDM and conventional ARQ system are compared in **Figure 13**. Two IRDM systems are presented in this figure. One uses two interleaving patterns and, hence, uses two soft symbol buffers at the receiver. The other uses three interleaving patterns and three receiver buffers. In high signal-to-noise ratio (SNR) regions, most frames can be received correctly without any retransmission. Hence, the IRDM systems behave similarly to the conventional system. However, because of their superior link-level performance, the IRDM systems may offer much higher through-puts than conventional system when the SNR drops as shown in the graphs. The improvements could be as high as 300%. Note that most of the through-put gains in the simulations are obtained by using only two interleaving patterns. Also note that, because the first pattern IP(1) is trivial, the IRDM system may use only one real interleaver.

Finally, the computational complexity of the IRDM system may be considered. In the above simulation for through-put, the maximum allowed number of differential demodulations were set to be 12 and 15 for the respective IRDM systems with two and three buffers, respectively. On average, however, the iterative algorithm terminates with a lesser number of demodulations used, as illustrated in **Figure 14**. **Figure 14** is a graphical illustration of average number of differential demodulation passes for IRDM systems according to embodiments of the present invention. For example, at C/N=10dB, on average, both IRDM systems activate the demodulator twice for each frame.

Once retransmissions occur, the illustrated embodiments of the present invention show improved link performance. For example, as shown in **Figure 14**, with two copies received at C/N=10dB, there is only an 8% chance shown that more retransmissions will be needed with the illustrated embodiments of the present invention while the conventional approach shown in **Figure 11** indicates a 30% chance of requiring more retransmissions.

Note that for the comparisons of **Figures 11-14**, the channel model considered is a frame-wise flat Rayleigh fading channel. That is, each transmitted frame is multiplied by a Gaussian distributed fading coefficient and the fading is independent from frame to frame. Furthermore, the simulations used to generate the graphs assume perfect channel estimation.

Operations of the present invention have been described with respect to the block diagram illustrations of **Figures 3** through **6** and the flowchart illustrations of **Figures 7** through **10**. It will be understood that each block of the flowchart illustrations and the

block diagram illustrations of **Figures 3** through **10**, and combinations of blocks in the flowchart illustrations and the block diagram illustrations, can be implemented by computer program instructions. These program instructions may be provided to a processor to produce a machine, such that the instructions which execute on the processor create means for implementing the acts specified in the flowchart and block diagram block or blocks. The computer program instructions may be executed by a processor to cause a series of operational steps to be performed by the processor to produce a computer implemented process such that the instructions which execute on the processor provide steps for implementing the operations specified in the flowchart and block diagram block or blocks.

Accordingly, blocks of the flowchart illustrations and the block diagrams support combinations of means for performing the specified acts, combinations of steps for performing the specified acts and program instruction means for performing the specified acts. It will also be understood that each block of the flowchart illustrations and block diagrams, and combinations of blocks in the flowchart illustrations and block diagrams, can be implemented by special purpose hardware-based systems which perform the specified operations or steps, or by combinations of special purpose hardware and computer instructions which will all be referred to herein as a "circuit." For example the iterative demodulator circuit **515** may be implemented as code executing on a processor, as integrated circuit devices, such as signal processors or custom chips, or as a combination of the above.

In the drawings and specification, there have been disclosed typical embodiments of the invention and, although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation, the scope of the invention being set forth in the following claims.